

Science & Technology

REVIEW

January/
February 2003

National Nuclear
Security Administration's
Lawrence Livermore
National Laboratory

Creating Primordial Plasma

Also in this issue:

- Helping the Marshall Islanders Regain Their Island Paradise
- Modeling Complex Living Systems in Three Dimensions

About the Cover

Basic science research is fundamental to Livermore's national security mission. Likewise, advances in basic research are an important outgrowth of that mission, especially when that research investigates the physical origins of the universe—a nuclear reaction of cosmic proportion. As part of an international collaboration, Livermore researchers are attempting to create quark–gluon plasma, a form of matter that is believed to have existed in the first moments following the big bang. Brookhaven National Laboratory's Relativistic Heavy-Ion Collider (RHIC) is the source of this primordial plasma, which scientists are trying to detect using the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX), shown on the cover. The report on this challenging basic science project begins on p. 4.



Cover design: Amy Henke

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on assuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Center of Biophotonics founded

Lawrence Livermore National Laboratory and the University of California at Davis (UC Davis) have announced the founding of the Center of Biophotonics. This new research center at UC Davis will use light at a variety of wavelengths and intensities to study difficult biological phenomena such as how DNA is created and repaired and how molecules move in cells. The goal is to apply the center's discoveries to practical ends such as fighting disease and bioterrorism.

Livermore and UC Davis collaborators introduced the center by showing off a portable pathogen detector. This instrument analyzes a small blood or breath sample with light to quickly determine if someone has been exposed to a pathogen in a bioterrorist attack or to a new infectious disease.

"Our hope is to bring the 'Star Trek' fantasy of quickly detecting and curing disease closer to reality," says Livermore's Dennis Matthews, who will head the new center. "That's a futuristic, science-fiction version of basically being able to noninvasively detect disease and, if possible, turn around and do something about it."

The center is funded by a \$52-million, 10-year grant from the National Science Foundation. It is one of six new science and technology centers funded in 2002 and collaborates on research and education with a dozen other universities and research centers, including Lawrence Berkeley National Laboratory, UC Berkeley, UC San Francisco, Stanford University, and Mills College in Oakland, California.

Developments in nanotechnology and a better understanding of how to use lasers make this an opportune time to bring together researchers to explore the medical and biological uses of light. According to Matthews, the center will focus, for example, on understanding how molecules move inside cells; simulating how light and matter interact; creating machines to detect disease pathogens, especially those that bioterrorists are likely to use; and developing ways to treat diseases with light.

Contact: Dennis Matthews (925) 422-5360 (matthews1@llnl.gov).

Livermore partner on sixth R&D 100 win

In addition to the five R&D 100 Awards that the Laboratory won in 2002 as the primary submitter (see *S&TR*, **October 2002**), Livermore won another of these prestigious awards as part of a four-institution team led by the National Center for Supercomputing Applications at the University of Illinois (Urbana-Champaign). The winning invention is the Hierarchical Data Format 5 (HDF5), a file format and software library for storing, managing, and archiving large and complex sets of scientific or engineering data.

HDF5 technology handles any type of data suitable for digital storage, no matter its origin or size. The technology is a

fast, portable input/output library that can store trillions of bytes of computational modeling data or millions of bytes of high-resolution electronic images. With the help of lower-level libraries, HDF5 enables hundreds or thousands of processors to operate in parallel and simultaneously write information to a single file.

HDF5 overcomes the limitations of rigid data models for storing and managing most current file formats and is expected to be compatible with future developments in computing and data storage.

Livermore researchers who assisted in developing HDF5 are Robb Matzke, Linnea Cook, Mark Miller, and Kim Yates. A research highlight on HDF5 is scheduled for *S&TR* in **April 2003**.

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What stardust could tell us

At this moment, the National Aeronautics and Space Administration's (NASA's) Stardust space bus is on its way to Wild 2, a comet orbiting the Sun. The space bus's mission is to collect stardust, remnants of stars that may be able to tell the story of our solar system's beginnings and possibly the origins of life.

When the Stardust space bus returns to Earth in February 2006, Livermore astrophysicists will play a key role in examining the collected stardust with a new \$5-million electron microscope being acquired with NASA funding by the Laboratory's Institute for Geophysics and Planetary Physics (IGPP), which is part of the international consortium involved in the Stardust mission.

John Bradley, IGPP director and a major participant in Stardust, says that one of the big questions Livermore scientists want to answer is whether the stardust from Wild 2 has the same makeup as stardust gathered from the stratosphere. And, says Bradley, "We will have a dedicated microscope specifically to examine these particles."

Launched in February 1999, Stardust is the first NASA space mission dedicated solely to collecting comet dust and will be the first to return material from a comet to Earth.

Wild 2 is 4 kilometers in diameter and has an elliptical orbit around the Sun between the orbits of Jupiter and Earth. In January 2004, when its orbit will bring Wild 2 closest to the Sun, samples of stardust will be collected in a low-density aerogel stored in panels on the NASA space bus. Interstellar stardust will also be collected. In all, researchers hope to gather a thousand particles weighing a total of less than a microgram. After these particles return to Earth, they will be distributed among the international astrophysics researchers for study.

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Translating Vision into Reality

FOR decades, Lawrence Livermore's often unheralded engineering crew has been "translating" physicists' doodles on napkins and complex equations on white boards into devices and entire facilities that fill some new or long-standing need. The National Ignition Facility, whose powerful lasers will create a thermonuclear explosion in a laboratory, is the most visible case in point at Livermore now. But other examples abound. Certainly the scientists in the High-Energy Physics Group would not be able to make the scientific advances they do in basic nuclear and particle physics without Livermore's crew of experienced engineers.

The article beginning on p. 4 is a testament to this capability. Livermore is part of a worldwide collaboration that is using the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory to try to create a quark-gluon plasma, a state of matter that scientists suspect existed during the earliest moments after the big bang. Livermore designed and oversaw construction and installation of the giant magnets in the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector, one of four complementary detectors around the collider's tunnel. The steel magnets weigh 3.6 million kilograms, and the detector incorporates comparably big, complicated engineering.

PHENIX had to be capable of measurements of unprecedented precision. The theory of fundamental particles and how they interact predicts that quarks can never be seen directly. Instead, scientists must infer their presence from the combined results of many measurements, such as particle momentum. Collecting these data requires that PHENIX's massive magnets create a large magnetic field parallel to the accelerated beams of gold ions in the central region of the detector and a field perpendicular to the beams on the detector's north and south arms. In addition, the magnetic field in the arms must go to zero in the beam region so that it does not deflect the trajectories of the ions in the accelerator. Fitting the detector in the tunnel required that the magnets generating these fields be as compact as possible.

The B Factory at the Stanford Linear Accelerator Center is another example of how Livermore's engineers make big



science happen. Like PHENIX, the B Factory, which includes the PEP-II electron-positron collider and the BaBar detector, was designed to answer questions related to our early universe: Why is there a preponderance of matter over antimatter in the universe? What happened during the big bang that caused so little antimatter to remain? Experiments at the B Factory are just now beginning to supply information that may answer these questions.

During the 1990s, nearly 200 Livermore specialists in accelerator technology and advanced manufacturing helped to design and produce major components for the B Factory. Perhaps the most complex were the high-power radio-frequency cavities for the collider—the most powerful of their kind ever built—that maintain electron and positron beams at their proper energy level.

PHENIX and the B Factory are opening new windows on the subatomic world, providing scientists with a more complete and accurate picture of the fundamental nature of matter and energy. Although few organizations could have undertaken these projects, Livermore is that rare breed with the capabilities necessary to meet the challenge. Our knowledgeable and experienced engineering staff comes through every time, translating a physicist's vision into reality.

■ Glenn Mara is deputy director for Operations. He was previously the associate director for Engineering.

A Question of Quarks

To learn more about the early universe, scientists are attempting to create a state of matter that hasn't existed since the first moments following the big bang.

INSIDE the accelerator, gold ions zoom toward each other at almost the speed of light. They crash together with enough force to melt the ions into a quark-gluon plasma. This hot, primordial quark soup is thought to have existed in the first millionth of a second after the big bang that created our universe. The entire universe, small though it was then, is thought to have been a quark-gluon plasma. As the universe began to expand and cool, the quarks and gluons bound together and have remained virtually inseparable ever since.

Whereas the alchemists of old tried to turn all sorts of materials into gold, modern-day physicists, including several from Livermore, are attempting reverse alchemy—turning gold into a different state of nuclear matter. By smashing gold ions together in the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, New York, they are working to free quarks and gluons and re-create a quark-gluon plasma on Earth.

The quark is the most elementary building block of matter. (See the box on p. 7.) By exchanging gluons—massless particles that make quarks stick together—groups of quarks constitute particles such as protons and neutrons. The binding force carried by both gluons and quarks is known as the strong force, and for good reason. Although theory says that at extremely high energy densities, protons and neutrons should dissolve into a quark-gluon plasma, no particle accelerator had been powerful enough to create the necessary conditions with high certainty.

The possibility of creating hot, dense nuclear matter by colliding large nuclei was first proposed in 1973 by several

Livermore physicists, including George Chapline and Edward Teller (*Physical Review D* 8, 4302–4308). They predicted that experiments using Lawrence Berkeley National Laboratory's Bevelac, then the most powerful particle accelerator for heavy nuclei, would probably result in the "production of matter in a new regime of temperature and density."

They recognized that "since the experiments explore regions very far from our experience, it is reasonable to expect surprises." In fact, they surmised that the main result of the experiment would be the "unexpected phenomena." That is what great science is often all about.

The Experiment Today

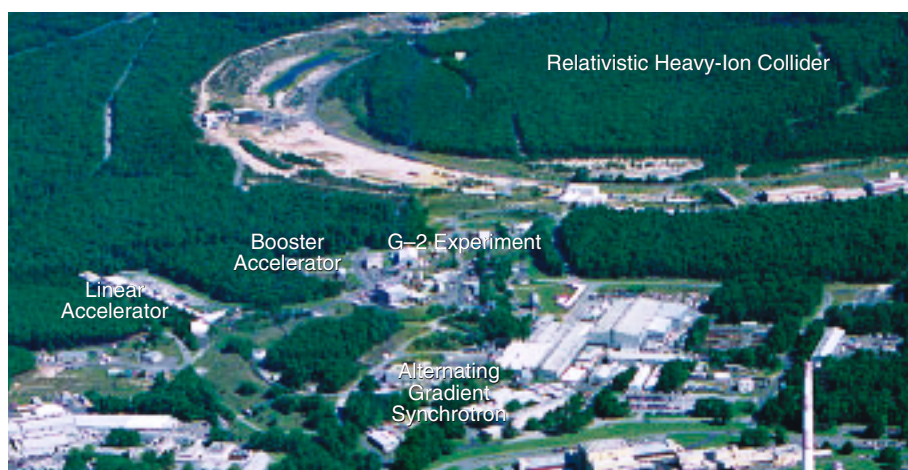
More than 25 years later, in 1999, physicists from institutions all over the world believed they might have finally established the laboratory conditions required to create not only the hot and dense region described in 1973 but also a new phase of matter. (See the box on pp. 8–9.)

Beams of gold ions or nuclei—atoms that have been stripped of their

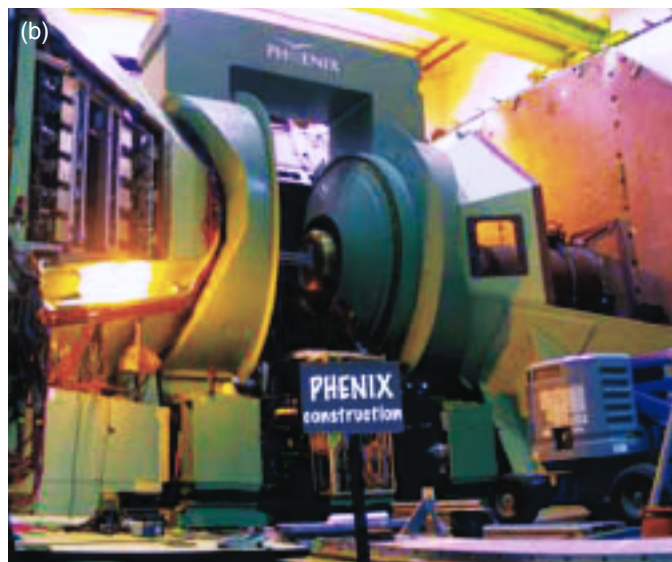
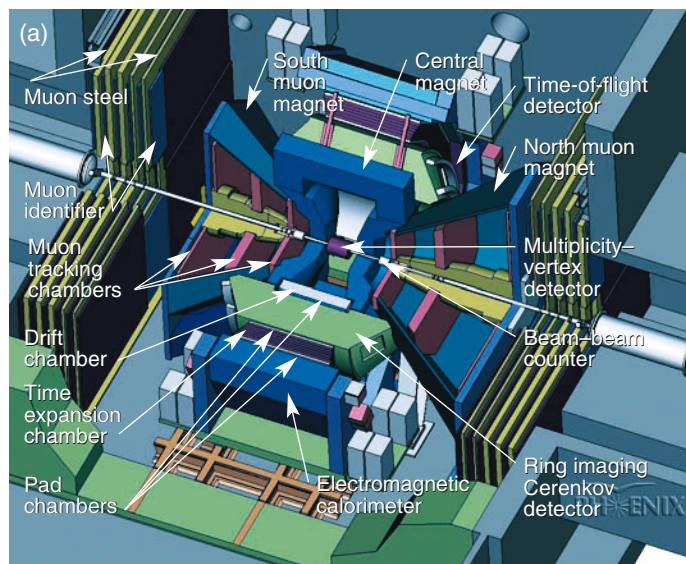
electrons—are propelled around RHIC's loops in opposite directions at 99.9 percent of light speed. When any two nuclei collide, the collision acts as a pressure cooker, liberating more than a trillion electronvolts of energy in a volume the size of an atomic nucleus. Some of the energy each nucleus had before the collision is transformed into intense heat and new particles such that new matter is created at a temperature

ten thousand times that of the Sun. The collisions are highly explosive, and if a quark–gluon plasma is created, it decays into particles (bound quarks) almost as quickly as the plasma is formed.

To determine whether a quark–gluon plasma existed during an experiment, scientists look for signatures in the distribution and composition of the particles that reach the Pioneering



Aerial photograph of the 3.8-kilometer-circumference Relativistic Heavy-Ion Collider and associated particle accelerators at Brookhaven National Laboratory.



(a) A schematic of the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector. (b) Inside the PHENIX detector.

High-Energy Nuclear Interaction Experiment (PHENIX) detector, which Livermore helped to design and build during the 1990s.

"If the experiment continues according to plan, we will have made a quark-gluon plasma," says Livermore physicist Ron Soltz, a principal investigator for Livermore's work at RHIC. "What we're essentially trying to do is find the boiling point of nuclear matter."

Measuring Success

Soltz's team, including physicists Stephen Johnson and Ed Hartouni and postdoctoral fellows Mike Heffner and Jane Burward-Hoy, are measuring the volume, lifetime, and violence of the collision zone (or source). A large volume and long lifetime are one of the purported signatures of a quark-gluon plasma. To take the measurements, the team examines the production of pions, a two-quark particle that is the most

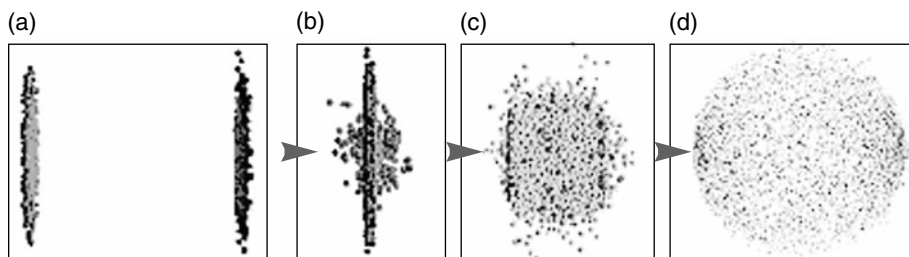
prevalent product of these collisions.

The team is exploiting a simple property of quantum mechanics, which is that the more highly correlated the pions are in a given direction, the larger the emission volume is along that axis. A long-lived source should appear as an apparent elongation of the fireball in the direction of the detector relative to the geometric radius of the fireball. The Livermore team found almost no elongation, in contradiction to most recent theoretical expectations.

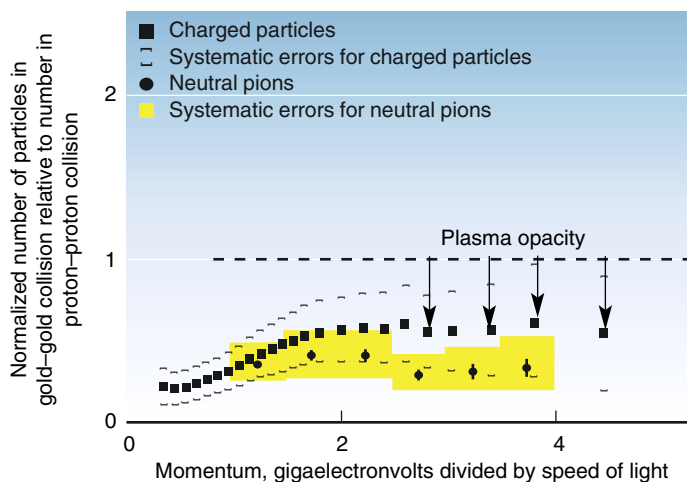
However, the story does not end there. Even before the Livermore team had finished its analysis, other collaborators were finding signs of the plasma in another signature.

"If no plasma is formed, particles with high momentum escape the collision unscathed," notes Johnson. "But if a quark-gluon plasma has been created, the interaction between high-momentum particles and the medium increases dramatically, significantly lowering the velocity of the particles."

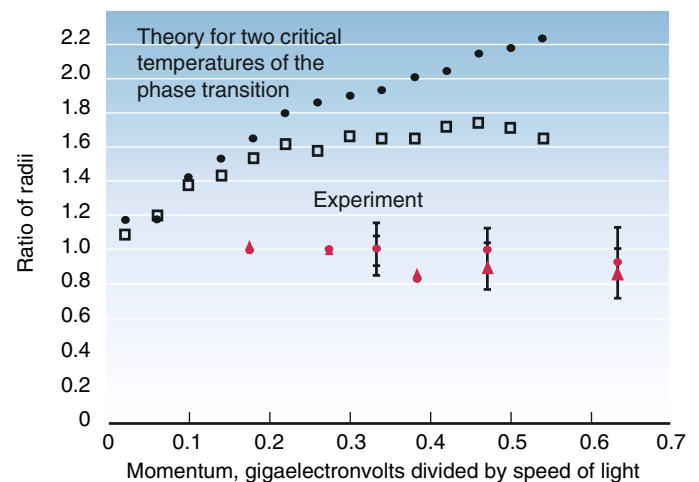
Quantum chromodynamics theory (see the box on p. 7) predicts that in the presence of a quark-gluon plasma,



(a) Inside Brookhaven's Relativistic Heavy-Ion Collider, two gold nuclei approach one another at almost the speed of light. Traveling at relativistic speeds causes them to look flat rather than spherical. (b) As the two nuclei collide and pass through each other, some of the energy they had before the collision is transformed into intense heat and new particles. (c) If conditions are right, the collision liberates the quarks and gluons in the nuclei to form a quark-gluon plasma. (d) As the area cools off, thousands more particles form. Many of these new particles will travel to a detector where their distinctive signatures give physicists clues about what occurred inside the collision zone.



A paucity of high-momentum particles during the collision of gold nuclei, which is the result of an opaque source, is consistent with theory and indicates the existence of a quark-gluon plasma.



Results from the STAR and PHENIX detectors show that the elongation of the collision zone (indicated by the ratio of two radii) was considerably less than theory predicted. In fact, there was no elongation at all, with ratios of about 1.

substantially fewer high-momentum particles will make their way to the detector. That relatively low number is, in fact, what PHENIX found by counting high-energy pions.

So right now, the data are inconclusive. “Obviously, we need more information,” says Soltz. “We’re considering two options at this point.

One is to study rarer particle signatures, which would require a lot of data that we don’t have. The other option is to go to a simpler experiment whose results will be easier to interpret.”

A Simpler Experiment

When two gold nuclei collide, many interactions occur between all of the

nucleons (protons and neutrons). Although these numerous interactions are responsible for creating the conditions necessary to form a quark–gluon plasma, researchers have difficulty differentiating between signals resulting from the plasma and those that may be caused by other interactions of the nucleons.

Atomic Parts and Particles

All things, living and inanimate, are made of atoms. Almost all of an atom’s mass is in its nucleus, where protons and neutrons reside. Protons and neutrons consist of various combinations of quarks. At the moment, scientists believe that quarks are the smallest particles in our universe and that they form the basis for all matter. However, just as scientists until the late 19th century believed that the atom was the smallest particle, they may someday discover particles smaller than quarks.

In the meantime, theory holds that quarks, with the help of gluons to hold the quarks together, make up everything in the nuclei of atoms. Up, down, charm, strange, top, and bottom—these are the six “flavors” of quarks. Up and down quarks are the least massive and are more prevalent than other types. Protons always have two up quarks and one down quark, whereas neutrons have two down quarks and an up quark. Other more exotic and more massive particles are composed of other quark combinations. A lambda particle, for example, has an up, a down,

and a strange quark, while a kaon has a strange and an up quark. Gluons carry the strong force that glues quarks together to form protons, neutrons, and other particles and keeps them together in an atom’s nucleus.

In contrast, the electron is not made of quarks and is not subject to the strong force. Instead, the electromagnetic force keeps an electron in its orbit spinning around an atom’s nucleus.

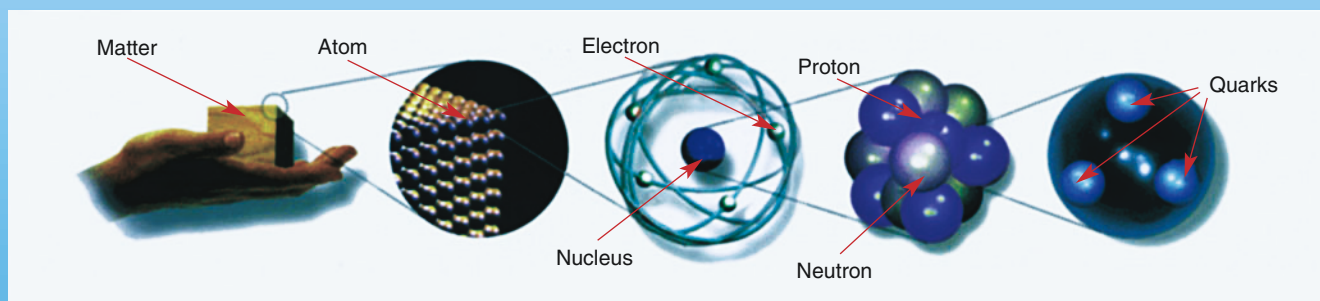
After discovering that the atom was not the most elementary particle, scientists realized that subatomic particles behave differently from larger, bulk quantities of matter. The field of quantum mechanics was developed to explain this apparently eccentric behavior.

Then they discovered quarks and gluons, whose existence was first inferred from the spectra of elementary particles and from electron-scattering experiments in particle accelerators. Quarks and gluons possess a type of charge that has been whimsically termed color. Color is the source of the powerful forces that first cluster the quarks and gluons to make

protons and neutrons and, in turn, grip these nucleons to one another to form atomic nuclei. A new theory, quantum chromodynamics, was developed late in the 1960s and early 1970s to describe these phenomena.

Quantum chromodynamics, which explains the strong force, bears many similarities to quantum electrodynamics, which explains electrical charges and light. Atoms can be ionized and the fundamental electrical charges of quantum electrodynamics can appear in isolation, but in quantum chromodynamics, the fundamental quark and gluon constituents of protons and neutrons can only be liberated in conditions identical to those of the big bang. This property of quark–gluon confinement gives stability to all matter as we know it.

Quantum chromodynamics theory predicts that deconfinement will occur at sufficiently high temperatures, nuclear densities, or both. Quarks and gluons will break free of their bondage in atomic nucleons, re-creating the earliest moments of our universe.



Simpler to study than the collision between two nuclei is a collision between a single proton and a nucleus. While one proton may have several interactions within a nucleus, scientists do not expect that these interactions will create a plasma. But exactly how many such interactions are there? Finding the answer to this question for each proton–nucleus collision will allow scientists to make proper comparisons with the results from nucleus–nucleus collisions. If scientists can measure the number of interactions, they should be

able to verify the underlying signatures of a quark–gluon plasma.

Under Johnson's leadership, the Livermore team has begun adding a detector to PHENIX that will make these measurements in proton–nucleus collisions. The new detector is a calorimeter that measures the pieces of the fragmenting nucleus after a proton has blasted through it. To provide this entirely new capability in short order at a minimal cost, the Livermore group adopted detectors and equipment from previous Brookhaven experiments. The

result is what they jokingly refer to as the "Scrounge-a-Cal." The calorimeter is being instrumented in PHENIX now, and the first results will be analyzed this spring.

Answering Quark Questions

Research at Brookhaven and elsewhere is beginning to answer some new and old questions about quarks. Researchers at the National Aeronautics and Space Administration's Chandra X-Ray Observatory recently discovered what appears to be a collapsed star with

PHENIX and RHIC Rise

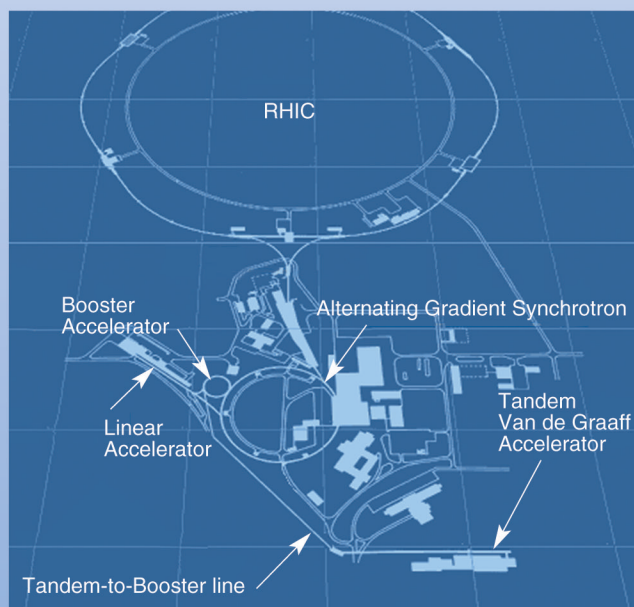
Only massive experimental equipment such as the Relativistic Heavy-Ion Collider (RHIC) and the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector at Brookhaven National Laboratory make it possible to study the almost infinitesimally small dot known as the quark.

An inverse relationship exists between the size of the object being studied and the

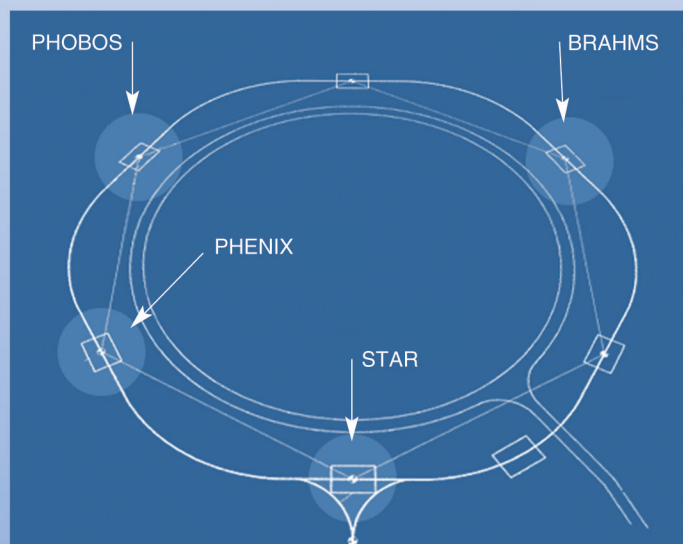
size and expense of the equipment needed to examine it: the smaller the object, the greater the energy needed to probe it, and thus, the larger the equipment required. Particle and nuclear physicists, who want to examine the fundamental building blocks of matter up close, need hugely expensive machines often measuring a kilometer or more in diameter. Given their expense and size, few such machines can

be built. Many nuclear and particle physicists must concentrate their efforts on the few particle accelerators and colliders available around the world.

Lawrence Livermore is just 1 of 55 institutions from 11 countries involved in the quark–gluon plasma experiments being performed on the PHENIX detector at Brookhaven. There are 450 scientists participating, each



A schematic of the Relativistic Heavy-Ion Collider (RHIC) complex.



The layout of the detectors around the RHIC tunnel.

a quark core. If accurate, this discovery complements the current search for the quark–gluon plasma at RHIC. It also confirms a prediction made 25 years ago by Livermore physicist Chapline about extremely dense stars with a quark–gluon plasma at their core rather than the bound quarks usually found in neutron stars.

Equally important—for basic science and a better understanding of how our universe got started—the experiments at Brookhaven’s RHIC hold the key to answering one of the questions posed

recently by the National Research Council Committee on Physics of the Universe. In its report, *Connecting Quarks with the Cosmos: 11 Science Questions for the New Century*, number 7 on the council’s list was “Are there new states of matter at ultrahigh temperatures and densities?” Livermore researchers and their collaborators hope to answer that question soon.

—Katie Walter

Key Words: Brookhaven National Laboratory, particle physics, Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector, quark–gluon plasma, Relativistic Heavy-Ion Collider (RHIC).

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Additional information on the Relativistic Heavy-Ion Collider is available at:
www.bnl.gov/RHIC

responsible for a different task in this challenging endeavor.

RHIC, which measures 3.8 kilometers in circumference, was commissioned in October 1999. It was the first colliding-beam facility specifically designed to accommodate the requirements of heavy-ion physics at relativistic, or speed-of-light, energies.

RHIC is actually the newest link in a chain of accelerators that make up the RHIC accelerator complex. Heavy ions destined for RHIC originate in a Tandem Van de Graaff Accelerator, proceed into the Booster Accelerator, and then into the Alternating Gradient Synchrotron, which injects heavy ions into RHIC for experiments. Before RHIC was completed, Livermore physicists contributed to major discoveries about the properties of nuclear matter using the Alternating Gradient Synchrotron.

When RHIC is operating, bunches of heavy ions can be injected into each of its two rings, which are in a tunnel. Then, with both rings filled, the ions are accelerated in minutes to the top energy where the ion beams coast for hours in stable orbits around the rings. The tunnel is configured so that the circulating ion beams can cross and collide in six places. Four of the six collision spaces now hold detectors that electronically record the results of the interactions between



The team celebrates completion of testing of the PHENIX detector.

particles. During experiments, particles are made to collide head-on at the rate of tens of thousands of collisions per second at the position of each detector, shown in the right-hand figure on p. 8. The two largest detectors are PHENIX and STAR. Two smaller detectors are known as PHOBOS and BRAHMS. Each detector uses different technologies to determine whether a quark–gluon plasma is present in RHIC.

A team of scientists from Lawrence Livermore and Brookhaven national laboratories developed the three powerful magnets in the PHENIX detector. Livermore was responsible for the design and supervised fabrication and testing of the magnets.

PHENIX weighs 3.6 million kilograms and has a dozen detector subsystems. The three magnets produce

high magnetic fields to bend charged particles along curved paths. Tracking chambers record hits along the flight path to measure the curvature and thus determine each particle’s momentum. Other subsystems identify the particle type and measure the particle’s energy with calorimeters. Still others record where the collisions occurred and determine whether a collision was head-on or peripheral.

Each type of particle has a distinctive mass and charge associated with it, which allows accurate identification. Each particle will bend and move differently in the magnetic field, allowing scientists to resolve the type of particle it is and its energy. By combining information from all detectors, scientists attempt to reconstruct what happened during the collision.



Island Paradise Regained

By developing ways to minimize radiation exposure from past atmospheric nuclear tests, Livermore helps Marshall Islanders regain their island paradise.

BETWEEN 1945 and 1958, the United States conducted 67 atmospheric tests of nuclear weapon designs on the Bikini and Enewetak atolls of the Marshall Islands. After this testing ended in the late 1950s, residents who had been relocated from these atolls began asking to return to their home islands.

But going home proved to be not so simple. At Enewetak, for instance, islands continued to be used for other defense programs through the 1960s and 1970s. Finally, in 1978, an extensive radiological survey was conducted of the northern Marshall Islands, including those in the Bikini and Enewetak atolls. An aerial survey determined the external gamma exposure rate. Samples of soil, food crops, animals, well water, seawater, fish, and more were collected to evaluate the radionuclide concentrations in the atoll environment. About the same time, the U.S. launched a massive cleanup and rehabilitation program on the Enewetak Atoll, scraping off about 76,400 cubic meters of surface soil from 6 islands and sealing it off in a crater on the atoll's Runit Island.

This cleanup focused primarily on removing and containing plutonium and other heavy radioactive elements from a group of islands in the northwest corner of the atoll where

most of the tests were conducted and the highest levels of local fallout were found. Yet, even during this early cleanup, questions arose about whether these efforts would be adequate to protect the returning Enewetak population. Predictive assessments based on the extensive radiological survey showed that ingestion of cesium-137 and other fission products from eating locally grown food and drinking the local water was the most significant exposure pathway. Cesium-137 fallout from the tests was more widely distributed than plutonium.

Islanders and scientists had already had an opportunity to discover what happened when islands were resettled without adequately addressing the ingestion portion of the equation. In 1969, the people of Bikini had resettled their home islands. Once the locally planted food crops had matured and island residents began including the resulting fruits in their diet, the amount of cesium-137 in their bodies (the "body burden") increased dramatically. The people of Bikini once again had to leave their islands and have yet to return.

The southern portion of the Enewetak Atoll was resettled in 1980. Today, scientists in Lawrence Livermore's Marshall Islands Dose Assessment and Radioecology Program

work to minimize exposure through ingestion and other pathways for the Marshallese now living on or wishing to return to their islands. The program, directed by Livermore environmental scientist Terry Hamilton, continues research begun nearly 30 years ago—characterizing radiological conditions on affected islands and developing strategies to minimize radiological exposure to a people wishing to resettle. The program also supports Marshallese efforts to implement radiation protection programs for residents wishing to track their exposure to radionuclides from fallout contamination that still lingers on the islands.

Doing the Groundwork

When islanders from Bikini and Enewetak—and, later, Rongelap—began asking questions about residual fallout contamination on their islands, U.S. officials decided that more knowledge of the conditions of the atolls was needed before resettlement could begin. (See box on [p. 17.](#)) Livermore scientists conducted large-scale environmental surveys of the radionuclide distribution to gather data for analyzing the health risks the island residents might face if they resettled. Questions to answer included: What would be the long-term radioactive

exposure from eating crops grown on the islands? From drinking the water? From eating fish caught in the lagoons?

For more than 25 years, Livermore scientists have collected over 70,000 samples of edible food crops, vegetation, soil, water, marine life, and animals to evaluate the various exposure pathways for radiological dose. They combined the radionuclide inventory from the samples, a diet model for the population, and biokinetic models to determine the dose due to ingestion. (See *S&TR*, January/February 1997, pp. 14–21.) At several atolls, they also evaluated external exposure to gamma radiation and studied how the resumption of human activity might cause nuclides in the surface soil to be resuspended in the air and thus inhaled. Results indicated that ingestion was the most significant exposure pathway, with external exposure to gamma radiation being the next most significant. The dose from ingestion contributed 70 to

90 percent of the dose to island residents, mostly through uptake of cesium-137 into island-grown foods such as coconut, pandanus, breadfruit, and papaya.

“One of the most significant things we discovered from this research is that the uptake of cesium-137 is very different for plants grown in Marshall Islands soils than for plants grown in North American and European soils,” says Hamilton. The uptake of cesium-137 in continental soils—the measurement used in most previous studies—is much lower. Such uptake can be expressed by the soil-to-plant transfer factor, that is the ratio of becquerels (units of radioactive activity) per kilogram of dry weight plant to becquerels per kilogram of dry weight soil. For cesium-137, the soil-to-plant transfer factors for tropical fruits grown on Bikini range between 2 and 40; for vegetation grown on continental soils in temperate zones, the factors range between 0.005

and 0.5. The reason for the difference lies in the different compositions of the soils.

Unlike continental soils, island coral soils have little clay and low concentrations of potassium. With no clay for the cesium to bind to and plants essentially starving for potassium, the plants take up cesium as a replacement for the potassium. “Once we knew this, we could more reliably predict the dose for returning residents and develop a strategy to limit the availability and uptake of cesium-137 into the crops,” says Hamilton.

Among the methods considered was removing contaminated soil that contains most of the cesium-137. However, the surface soil layer supplies all the nutrients for plants and controls the amount of water held in the soil. Removing this top layer wholesale would lead to severe environmental effects and a long-term commitment to rebuild the soil and revegetate an island.



Livermore's environmental scientists continue work begun more than a quarter century ago in the Marshall Islands, assessing and evaluating the various exposure pathways for radiological dose and developing ways to limit the dose. (a) Experiments to reduce the uptake of cesium-137 by coconut trees and other food crops have been conducted on Bikini Island. (b) Fish collected on annual sampling trips are analyzed for radionuclides at Livermore.

After examining other methods for eliminating cesium from the soil or reducing its uptake into food crops, the team settled on a remediation technique of applying potassium fertilizer and using limited soil removal in housing and village areas. It developed this method on results of large-scale field experiments conducted by Livermore on Bikini Island. The added potassium reduces the cesium-137 taken up by plants by nearly 90 percent, lowering the associated ingestion dose to about 5 to 10 percent of the pretreatment levels. The fertilizer has an added benefit as well—supporting the growth and increasing the productivity of the plants.

In 2000, when activities began to prepare Rongelap Island for resettlement planned for 2003, scientists

took the agricultural fix developed on Bikini and combined it with a procedure designed to reduce external exposure rates and inhalation or ingestion of contaminated soil containing plutonium. This procedure involves removing surface soil down to about 25 centimeters in and around the housing and village areas and replacing it with crushed coral. A detailed in situ gamma radiation survey of the entire area, conducted during May 2001 by Livermore scientists, found that the average external dose from cesium-137 within the service and village areas was reduced by more than 20-fold to less than 1 millirem a year. To put this dose in perspective, the average person in the U.S. receives a dose of about 46 millirems per year from natural terrestrial gamma radiation.

The results of the fertilization work on Rongelap are still pending, although the data from monitoring resettlement workers suggest that internal doses from cesium-137 ingestion in the resettled population will be extremely low. “In this case,” says Hamilton, “the use of potassium will, we hope, provide an added assurance to the people that the island is suitable for resettlement.”

Hamilton added that, for the islanders who return, the situation should only improve with time. Rainfall transports cesium-137 out of the root zone of plants and into the groundwater. In the longer term, this will reduce cesium-137 levels in local food crops and reduce dose estimates even further. Livermore researchers are now exploring how long the beneficial effects of a single potassium treatment lasts and evaluating the rate of environmental loss of cesium-137 in the atoll ecosystem as a whole.

Determining Each Person's Dose

Another goal of the Livermore effort is developing individual radiation protection programs that ensure doses to island residents remain at or below acceptable safety standards. The cornerstone of this activity rests on

whole-body counting systems and a new Livermore-developed technique to measure extremely small amounts of plutonium in urine.

Whole-body counting systems measure the gamma rays coming from radionuclides such as cesium-137, cobalt-60, and potassium-40 deposited in the body and internal organs. The total amount of a radionuclide measured in this manner is converted into a dose estimate using specially designed commercial software. Hamilton explains that the main pathway for exposure to residual fallout contamination in the northern Marshall Islands is through ingestion of cesium-137, and whole-body counting is a simple and effective method for determining the quantity of cesium-137 taken up by an individual. “This part of the program offers island residents an unprecedented level of radiation protection monitoring,” he adds. “With these systems in place, residents don’t have to rely on assumptions made about their intake of locally grown foods. They get real measurements on a person-by-person basis.” When measurements are combined with environmental monitoring data, individuals can make informed decisions about eating habits and lifestyle.

Local Marshallese technicians trained at Lawrence Livermore operate whole-body counting facilities on Rongelap and Enewetak. Livermore scientists provide technical assistance and advanced training and perform detailed quality assurance appraisals on the data before they are released.

Plutonium urinalysis is a sensitive measurement technique for estimating a person’s exposure to plutonium. Urine is collected from an individual over a 24-hour period and turned into a powder that scientists analyze by counting the number of plutonium atoms in a sample. “All of us have a small amount of plutonium in our bodies from exposure to worldwide



Plates inserted into soil collect water that will help scientists determine the removal rate of radionuclides due to rainfall. One area of current research in the Marshall Islands involves determining the environmental factors that remove radionuclides from the immediate environment. For instance, rainfall is leaching cesium-137 from the soil into the groundwater and out into the lagoons. Scientists are discovering that this process is actually more important than radiological decay in decreasing the dose over time.

Fallout from History

The story of fallout and its repercussions in the Marshall Islands can be summed up by looking at events in three of the northern atolls—Bikini, Enewetak, and Rongelap.

Soon after World War II ended, the United States examined several possible locations for conducting tests for its growing nuclear weapons program. The coral atolls in the northern Marshall Islands in the Pacific Ocean appeared to offer the best advantages of stable weather conditions, fewest inhabitants to relocate, isolation, and—with hundreds of miles of open ocean to the west—minimum radioactive fallout onto populated areas. Residents were relocated from islands in the Bikini and Enewetak atolls before testing began.

The most significant contaminating nuclear test conducted in the Marshall Islands was the Castle-Bravo Event on March 1, 1954. The explosive yield of Bravo exceeded expectations and resulted in unexpected radioactive fallout over the inhabited islands of the Rongelap and Utirik atolls and other areas east of Bikini.

Before Bravo, little consideration was given to the potential health and ecological effects of fallout contamination beyond the immediate vicinity of the test sites. Sixty-four

people on Rongelap received significant exposure from Bravo and had to be evacuated for medical treatment. The Rongelap community spent the next three years living on Ejit Island in the Majuro Atoll before returning home in 1957.

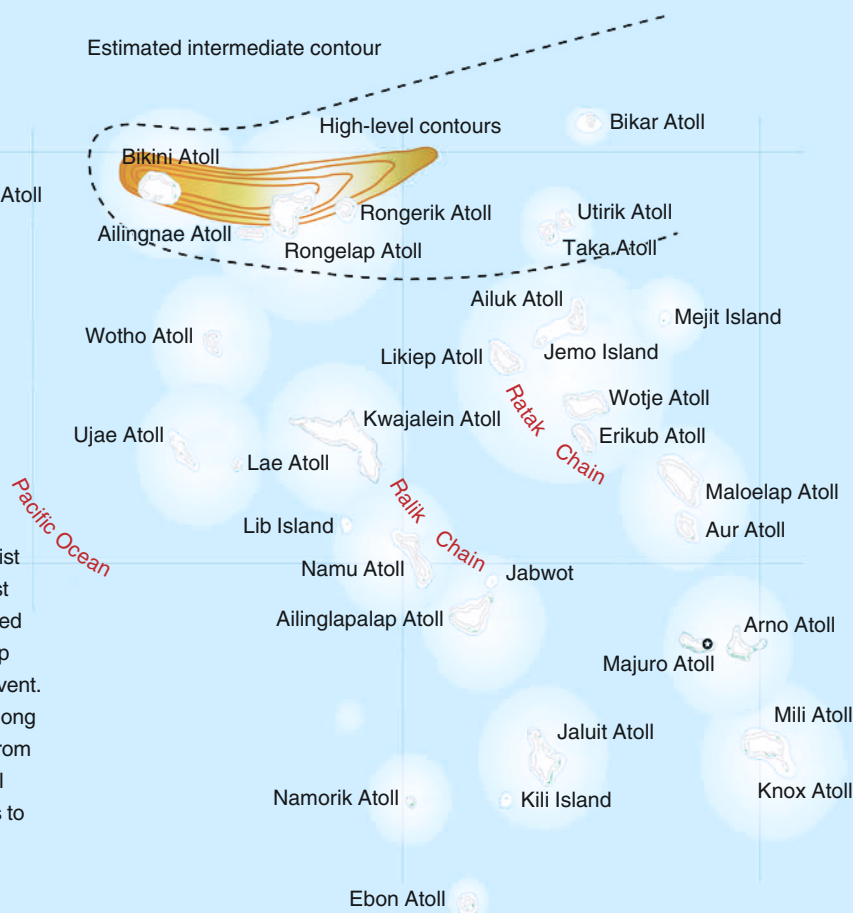
Rongelap was the first atoll to experience an early wave of resettlement. Bikini was next, with islanders settling on their homelands in 1969, planting food crops, and returning to their island lifestyle. But trouble bloomed in paradise. Once the planted food crops in Bikini matured and started to produce fruit, the fruit became part of the inhabitants' diets, and the amount of cesium-137 in the Bikini residents' bodies increased dramatically. In 1978, the people of Bikini left their islands a second time. A similar turn of events occurred in Rongelap, where growing concerns about the possible health effects of exposure to residual fallout contamination prompted residents to relocate again in 1985. The Rongelap community continued to

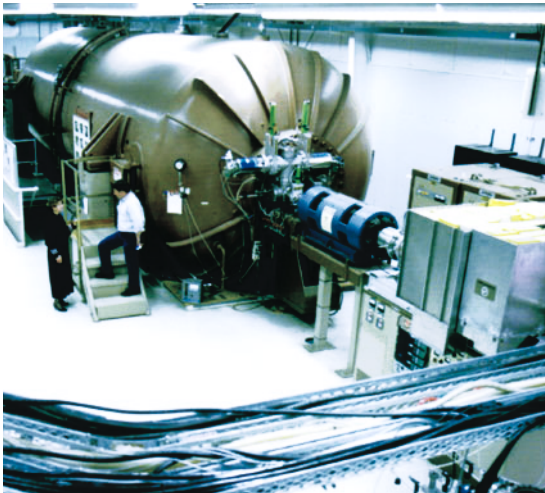
express a strong desire to return. In 1996, the U.S. Congress approved a resettlement agreement that included an initiative to reduce the level of radiation exposure on the island using a cleanup strategy developed by Livermore scientists.

As for Enewetak, it continued to be used for defense programs until cleanup began in 1977. The southern part of Enewetak was successfully resettled in 1980, and islanders continue to live there. From 1980 to 1997, scientists from Brookhaven National Laboratory periodically monitored the resettled population for internally deposited radionuclides, a program that then moved under the purview of Lawrence Livermore.

The work on the Marshall Islands continues, with Livermore playing a number of key roles, including characterizing the radiological conditions at the various atolls; determining the transport, uptake, and cycling of radionuclides in the ecosystem; and estimating the potential radiological doses and risk.

The Republic of Marshall Islands consists of 34 atolls scattered over 1.3 million square kilometers and clustered in two main groups: the Ratak and the Ralik chains. The atolls consist of numerous coral reefs. Kwajalein is the largest atoll, and Majuro is the capital island. The dashed line and shaded areas near Bikini and Rongelap atolls show the fallout pattern from the Bravo Event. The Rongelap and Utirik communities were among those relocated after being exposed to fallout from Bravo. The Utirik community returned to its atoll about three months after the test and continues to inhabit the atoll today.





Livermore's new technology to measure extremely small amounts of plutonium isotopes and other long-lived radioisotopes came out of research conducted at the Center for Accelerator Mass Spectrometry. This sensitive measurement technique has possible applications beyond the Marshall Islands work, in areas such as nuclear isotopic forensics and counterterrorism, risk assessments, and dose reconstruction for exposed nuclear workers.



Marshallese technicians trained at Livermore run whole-body counting facilities on Rongelap and Enewetak. The facility at Enewetak is shown below in the background.

fallout contamination," notes Hamilton. "The Livermore team's job is to compare the amount of plutonium detected in Marshall Islands residents with that seen elsewhere to assess likely intakes associated with resettlement."

Plutonium urinalysis can detect extremely small amounts of plutonium. The technique, developed at Livermore's Center for Accelerator Mass Spectrometry as part of a Laboratory Directed Research and Development project, is about a hundred times more sensitive than techniques used in U.S. occupational monitoring programs. Data from the studies show that residents' and island workers' exposures to plutonium are low. "People get a higher dose of radiation taking an airplane from the Bay Area to one of these islands than they get while working there," says Hamilton.

A recent comparison exercise organized by the National Institute of Standards and Technology for determining low-levels of plutonium in synthetic urine gave high marks to the mass spectroscopy technique. In fact, Livermore's laboratory was the only one to meet the American National Standards Institute (ANSI) quality performance criteria for both precision and bias at all test levels.

Over the past three years, memorandums of understanding between the U.S. Department of Energy, the Republic of the Marshall Islands, and the Enewetak-Ujelang and Rongelap Local Atoll Government

have been signed, leading to the design and construction of radiological laboratories on Enewetak and Rongelap atolls. A third facility is slated for construction in 2003 on the capital island of Majuro and will be available to residents of Utirik and other outlying islands.

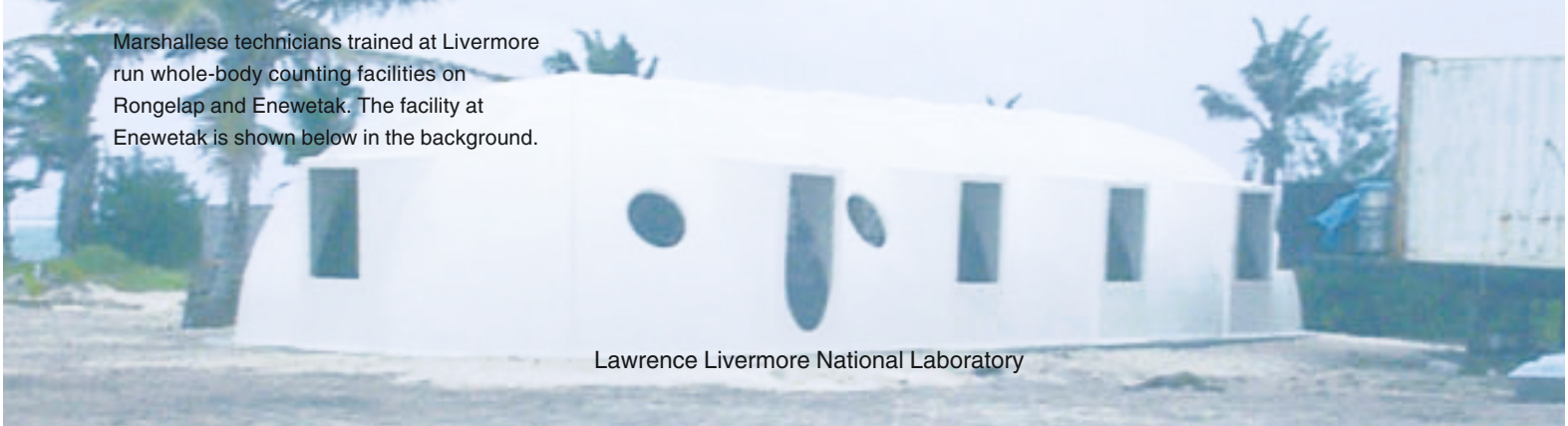
Going Home

"In the Marshall Islands, societal fear of radiation conflicts with a desire to resettle native homelands," concludes Hamilton. "The work the Livermore team is doing—providing environmental measurement data and dose assessments—has the goal of finding ways to minimize the exposures of returning residents. First, there is the remediation. Then there's whole-body counting and the accelerator mass spectrometry measurements. As communities return and settle into these islands, we hope that the programs will provide a level of reassurance to the residents that the amount of radiation they receive is small—well below the standards set by their own government—and becoming smaller."

—Ann Parker

Key Words: accelerator mass spectrometry, Bikini Atoll, Bravo Event, Center for Accelerator Mass Spectrometry (CAMS), cesium-137, dose assessment, Enewetak Atoll, Marshall Islands resettlement, Nuclear Test Program, plutonium, Rongelap Atoll, whole-body counting.

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Lawrence Livermore National Laboratory

Understanding Cells in a New Way with Three-Dimensional Models

THE recent completion of the Department of Energy's Human Genome Project indicates the remarkable progress scientists have made in understanding the genetic basis of life. The Genomes to Life Program, the successor to the Human Genome Project, has an even more ambitious goal: to understand life in a comprehensive and integrated manner. The initiative is an example of systems biology, the study of tissues as integrated systems rather than as isolated parts, such as individual genes, proteins, or chemical reactions.

"Decades of experiments on isolated chemical pathways or proteins laid the foundation for the study of complex biological systems. Now, the increasing interest in systems biology reflects the fact that we do not yet have a comprehensive understanding of how a cell functions," says Livermore physicist Andrew Quong. He says that progress in systems biology requires a multidisciplinary effort involving experts in biology, biochemistry, molecular biology, chemistry, physics, and computer science. "Only when experts from various disciplines work together on a computational model can we begin to understand the interactions between genes and the thousands of subcellular components and chemical reactions, many of them linked in subtle ways to one another," says Quong.

Ultimately, advanced computational models—based on sound chemical and physical principles and new laboratory experiments—running on the fastest supercomputers will permit scientists to visualize and understand the complex interactions and changes within a simulated cell. For example, a scientist will one day be able to predict a cell's response to different mixes of nutrients or exposure to a drug or a toxin from a pathogen.

Quong notes that widely used, but relatively simple circuit diagrams treat cellular processes as dimensionless electrical circuits. Previous attempts at computational models have treated only a small set of chemical reactions. By contrast, Livermore scientists use models that combine many more reactions, and, where possible, they extend the simulations to realistically portray a cell in three dimensions.

Quong's project is to develop a three-dimensional (3D) model of calcium ion transport within epithelial cells, which line all body cavities, including the lungs, digestive track, and

kidneys. The research is funded by the Laboratory Directed Research and Development program. Calcium ions are fundamental signaling ions in cells and play a role in many cellular processes, from cell division to muscle contraction. Quong's research is among the first attempts at modeling cellular processes to take advantage of massively parallel supercomputers, which use many microprocessors working in tandem.

The research builds on Livermore's experience in computational biology, supercomputing, biosecurity, and multiscale modeling of materials and chemical reactions. The effort also involves laboratory experiments done by Livermore biologists to supply essential data for the developing model.

The immediate payoff from the research will be increased understanding of a key cellular function, but the Livermore team hopes that the model will lead to new insights into the interactions between pathogens (viruses or bacteria) and human host cells. These insights will likely result in advances to control and prevent disease as well as initiatives in homeland security to detect and thwart any attempt at biological terrorism.

Learning from High Explosives

Quong's team is modeling the flow of calcium ions inside kidney epithelial cells using ALE3D, a computer code originally developed at Lawrence Livermore for studying the detonation of high explosives. ALE3D is part of the family of codes belonging to the Advanced Simulation and Computing program, an element of the National Nuclear Security Administration's Stockpile Stewardship Program to ensure the safety and reliability of the nation's nuclear deterrent.

A code for high explosives might not seem applicable for mimicking cellular processes. However, the code's flexibility allows it to model chemical reactions and ions within a cell much as it tracks chemical reactions and the transport of molecules and ions created by chemical explosives.

Team member and chemist Albert Nichols notes that the chemistry and underlying physics in both a functioning cell and a high-explosives detonation are the same. Some adjustments must be made, however, for enzymes, which are not found in inorganic systems. Nichols also points out that in models of

purely chemical systems, reactions move toward thermodynamic equilibrium, whereas in a cell, equilibrium means death.

For the cell study, ALE3D tracks waves of calcium ions within a 3D mesh that corresponds to the volume of several adjoining epithelial cells. "Our goal is to track the flow of calcium ions at any point in space inside the cell," says Quong.

Epithelial cells are barriers that protect the body from the external world and inhibit and control the movement of water, molecules, and ions across these barriers. Quong notes that a pathogen's first interaction with a human is with epithelial cells,

so understanding the signaling and ion transport pathways in these cells has important applications to human health and protecting against bioterrorist attacks.

From among the large family of different epithelial cells, the team decided on those found in the kidney. These cells can be grown easily in culture. Also, they have a roughly cubic shape, with one highly specialized side facing the outside environment. This asymmetric design can be represented realistically with ALE3D.

Focus on Calcium Waves

In simulating the transport of calcium ions in kidney epithelial cells, the model includes the movement of inositol-1,4,5-triphosphate (called IP_3) molecules because they coordinate the release of calcium ions in waves. The waves, lasting several seconds each, are believed to be an important signaling mechanism as they move within and across epithelial cells. By binding to receptors, which are folded proteins located within the cell, IP_3 molecules trigger the release of calcium.

Although there have been other models of calcium waves, they have been limited to one or two dimensions. Says Quong, "We're constructing for the first time a 3D model that is consistent with experimental data and is based upon valid physiology and chemistry."

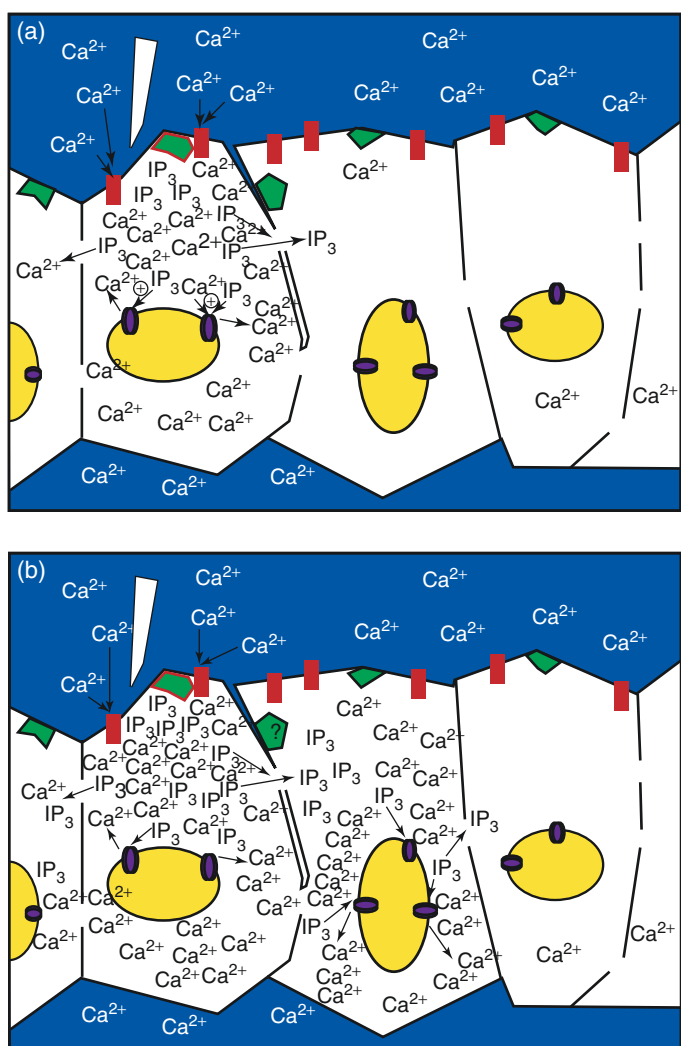
One goal of the Livermore model is to accurately reflect where calcium is stored within the cell prior to being released as part of a wave. Calcium ions are often found sequestered in certain organelles, specialized cell parts analogous to organs. A series of laboratory experiments on kidney epithelial cells, grown by Livermore molecular biologist Michael Thelen, will reveal the location of calcium-containing organelles.

The experiments will use antibodies labeled with fluorescent dyes to measure and visualize the calcium. The data will then be fed into the model.

Experiments Underpin Model

Thelen is also planning to image live cells with a confocal microscope. This type of microscope focuses light in a narrow plane, thereby allowing images of progressively deeper slices through a live cell. The observations will be compared with those gathered from secondary ion mass spectrometry (SIMS) imaging. (See the box on p. 17.)

Although the model is still incomplete, Quong has successfully used it to perform simulations based on published data from laboratory studies of kidney epithelial cells. The simulations model a group of several cells measuring about 25 micrometers in diameter. They show the initiation of calcium waves within a single cell and the propagation of the waves through neighboring cells. The simulations, with a resolution of about 1 micrometer, were completed on several Livermore supercomputers processing in parallel.



Waves of calcium ions are believed to be an important signaling mechanism as they move within and across epithelial cells. The waves are coordinated by inositol-1,4,5-triphosphate (IP_3), which binds to certain cell receptors. The diagram illustrates the flow of calcium and IP_3 molecules from (a) one cell to (b) its neighbors.

Visualizing Chemistry

Systems biology demands innovative experiments and instrumentation. Although not new to chemists, secondary ion mass spectrometry (SIMS) is beginning to be applied by biologists. With its extreme sensitivity (a few parts per billion) and spatial resolution (50 to 100 nanometers), SIMS is a powerful technique.

SIMS uses a stream of energetic ions that bombard the surface of a material under investigation. Upon impact, these ions generate positively and negatively charged ions, which are gathered by electrically charged lenses, imaged, and identified.

Secondary ion mass spectrometers are typically used in industry to characterize materials and to examine the surface of semiconductors and polymers. Livermore's three machines are used to map the surfaces of mirrors and optics for the Department of Energy's National Ignition Facility, now under construction at Livermore.

SIMS is unique because it can yield a map of any selected molecules or ions of interest. This is an important feature for biological applications because the alternative in many cases requires homogenizing many cells and then testing

for the presence of the molecules or ions. The result is an average of a cell population, with no information about location within a cell.

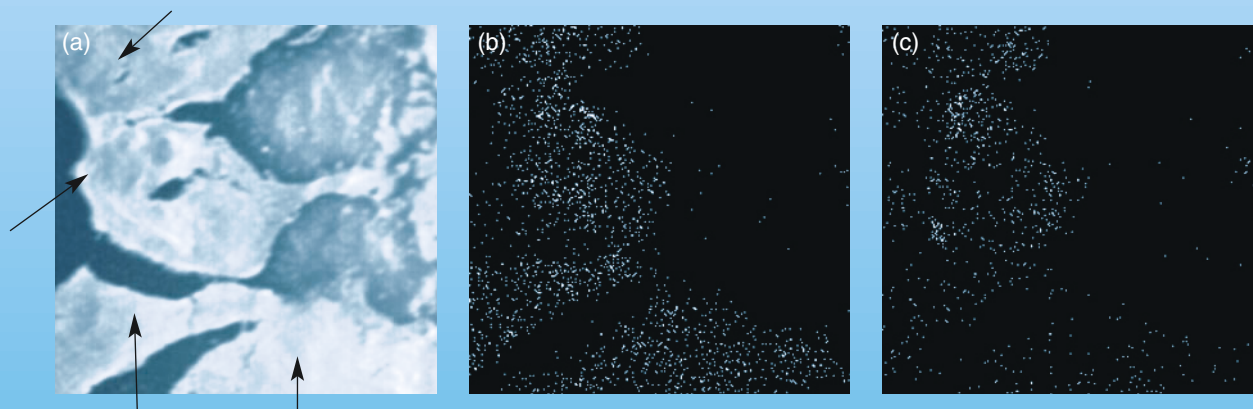
"Biological processes are dependent upon spatial localization," says Livermore biochemist Judy Quong. Quong is the principal investigator of a Laboratory Directed Research and Development project studying the application of SIMS to subcellular imaging. One area of research seeks to determine the distribution of PhIP (2-amino-1-methyl-6-phenylimidazo[4,5-b]pyridine) in cells. One of the mutagenic compounds known as heterocyclic amines, PhIP is a carcinogen that has been consistently demonstrated to cause dose-dependent mammary and prostate tumors in rats. Another area of research is using SIMS to determine the spatial resolution of isotopically labeled cancer drugs in cells. Improved understanding of the distribution of PhIP and cancer drugs in cells could lead to more effective cancer treatment.

Working with physicists Ian Hutcheon and Kuang Jen Wu, Quong uses two different mass spectrometers, a recently acquired static time-of-flight secondary

ion mass spectrometer and a dynamic secondary ion mass spectrometer. The Laboratory will be acquiring a new nanoscale dynamic secondary ion mass spectrometer (NanoSIMS), which has a spatial resolution of 50 to 100 nanometers and greater sensitivity than Livermore's current dynamic instrument. NanoSIMS will be only the second such machine in the nation dedicated to biological research.

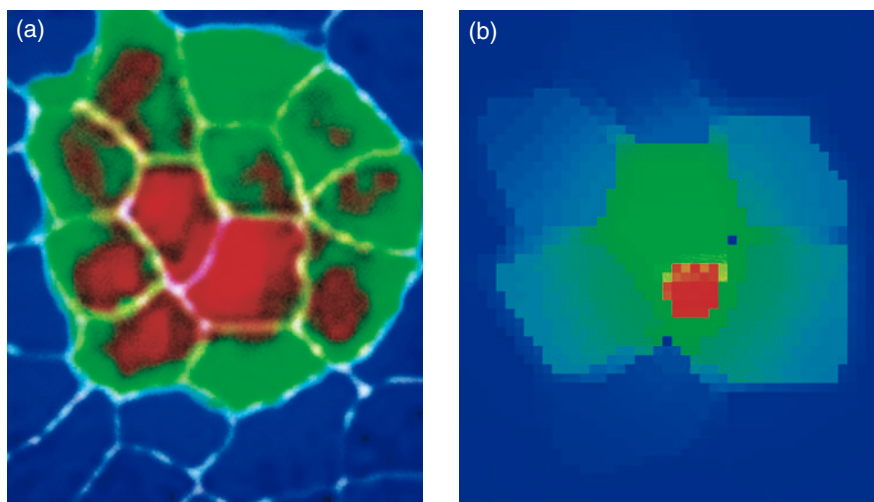
Because SIMS can detect any element, it is an ideal technique for helping physicist Andrew Quong's team locate calcium that is sequestered in cellular organelles, specialized cell parts analogous to an organ. SIMS will be able to generate a horizontal and vertical profile of the calcium distribution within frozen cells. The results will be compared to those gained from standard laboratory methods that use radioisotopes in live cells to locate calcium.

Biochemist Quong says she is hopeful that more Livermore biologists will take advantage of SIMS's capabilities. "We're trying to introduce biologists to new techniques that are normally used only by chemists and materials scientists."



To locate the three-dimensional position of calcium ions before they are released in a wave, the modeling team will be using secondary ion mass spectrometry (SIMS). Unlike electron microscopy, SIMS can detect any ion or molecule of choice, as seen in these images. (a) A scanning electron microscope image of clusters of human epithelial cells indicated by the arrows. Although the image shows the morphology of the cells, it cannot reveal the presence of selected molecules. (b) An image of the same cells taken by a secondary ion mass spectrometer shows the location of phosphocholine, a molecule found in cell membranes. (c) A SIMS image of the same cells shows that the PhIP mutagen is also present in this cell membrane.

A Livermore code simulating the flow of calcium ions compares favorably to experimental images of calcium ion waves. (a) An image from confocal microscopy taken by Japanese scientists captures a wave of calcium ions (bound to a red dye) that began in one epithelial cell and spread to its neighbors. (Image reprinted with permission from *Science* **284**, May 28, 1999, 1529. Copyrighted 1999, American Association for the Advancement of Science.) (b) The Livermore code simulates a wave of calcium ions (in red) triggered by the cell located in the center. The simulated cells measure about 25 micrometers across. The white lines represent cell membranes and the missing portions indicate gaps in the membrane where calcium ions pass from one cell to another.



Understanding the flow of ions in epithelial cells may help scientists treat kidney and lung diseases, says Quong. For example, calcium concentration affects the movement of cilia (tiny brushes) that are found in lung epithelial cells. The cilia catch and move pathogens and foreign particles that are trapped in mucus secreted by the cells. However, people suffering from cystic fibrosis, the most common genetic defect among Caucasians, produce abnormally thick mucus that can make breathing difficult and inhibit the movement and effectiveness of the cilia. The thick mucus is believed to be caused by the faulty transport of sodium and chloride ions in and out of the cells. This variable of ion transport will be incorporated into the model.

Biology's New Approach

The Livermore model is pointing the way toward a new approach to understanding how cells operate and diseases begin and progress. The eventual result will likely make the biological sciences more predictive. "A cell has so many interacting pathways that we must understand how everything is related, and computational models can help us do that," says Quong.

Advanced models of chemical pathways in the cell are important to both human health and national security. Indeed, the research directly supports Livermore's national security mission by helping scientists study issues related to biosecurity, such as the effects of pathogens on cell function and host-pathogen interactions.

"Our long-range goal is to develop tools for homeland security and health care," Quong says. Understanding the interactions between a host cell and a pathogen will help scientists learn how to shut off bacterial toxin production, defeat genetically engineered organisms, defend against new antibiotic-resistant microbes, predict a host cell's response to infections, defend agriculture against pathogens, and develop new drug delivery systems.

Computational models, once reserved for phenomena such as explosions and material fracture but now used for cells and their processes, are sure to become an important tool for scientists, health professionals, and those guarding our national security.

—Arnie Heller

Acknowledgments: The 3D epithelial cell modeling team consists of Michael Colvin, Aaron Golumbskie, Kenneth Kim, Alison Kubota, Christopher Mundy, Albert Nichols, Andrew Quong, Judy Quong, and Michael Thelen.

Key Words: Advanced Simulation and Computing program, ALE3D code, biosecurity, calcium ion waves, confocal microscope, cystic fibrosis, Genomes to Life Program, homeland security, Human Genome Project, secondary ion mass spectrometry (SIMS), systems biology.

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Patents

Microfabricated AC Impedance Sensor

Peter Krulevitch, Harold D. Ackler, Frederick Becker, Bernhard E. Boser, Adam B. Eldredge, Christopher K. Fuller, Peter R. C. Gascoyne, Julie K. Hamilton, Stephan P. Swierkowski, Xiao-Bo Wang

U.S. Patent 6,437,551 B1

August 20, 2002

A microfabricated instrument for detecting and identifying cells and other particles based on alternating current (ac) impedance measurements. The microfabricated ac impedance sensor includes two critical elements: a microfluidic chip, preferably of glass substrates, containing at least one microchannel and with electrodes patterned on both substrates; and electrical circuits that connect to the electrodes on the microfluidic chip and detect signals associated with particles traveling down the microchannels. These circuits enable multiple ac impedance measurements of individual particles at high throughput rates with sufficient resolution to identify different particle and cell types as appropriate for environmental detection and clinical diagnostic applications.

Device for Wavefront Correction in an Ultra High Power Laser

Earl R. Ault, Brian J. Comaskey, Thomas C. Kuklo

U.S. Patent 6,438,151 B1

August 20, 2002

A system for wavefront correction in an ultrahigh-power laser. As the laser medium flows past the optical excitation source, the fluid warms, and its index of refraction changes, creating an optical wedge. A system is provided for correcting the thermally induced optical phase errors.

Formation of Nanometer-Size Wires Using Infiltration into Latent Nuclear Tracks

Ronald G. Musket, Thomas E. Felter

U.S. Patent 6,444,256 B1

September 3, 2002

Nanometer-size wires having a cross-sectional dimension of less than 8 nanometers with controllable lengths and diameters are produced by infiltrating latent nuclear or ion tracks formed in trackable materials with atomic species. The trackable materials and atomic species are essentially insoluble in each other; thus, the wires are formed by thermally driven self-assembly of the atomic species during annealing, or recrystallization, of the damage in the latent tracks. Unlike conventional ion track lithography, this method does not require etching of the latent tracks.

OCDR Guided Laser Ablation Device

Luiz B. Da Silva, Bill W. Colston, Jr., Dale L. James

U.S. Patent 6,451,009 B1

September 17, 2002

A guided laser ablation device that includes a multimode laser ablation fiber surrounded by one or more single-mode optical fibers, which are used in imaging the laser ablation area. The laser ablation device is combined with an optical coherence domain reflectometry (OCDR) unit and a control unit. This control unit

initializes the OCDR and the high-power ablation laser and analyzes OCDR data for use in controlling the high-power laser. The OCDR images up to 3 millimeters ahead of the ablation surface to enable a user to see sensitive tissue, such as a nerve or artery, and prevent damaging it with the laser.

Electrostatic Particle Trap for Ion Beam Sputter Deposition

Stephen P. Vernon, Scott C. Burkhart

U.S. Patent 6,451,176 B1

September 17, 2002

A method and apparatus for intercepting, trapping, or reflecting charged particulate matter generated during ion-beam sputter deposition. The apparatus consists of an electrostatic particle trap that generates electrostatic fields near the substrate on which target material is being deposited. The electrostatic particle trap has an array of electrode surfaces, each maintained at an electrostatic potential and facing parallel or perpendicular to the surface of the substrate. These electrostatic fields are configured to force the charged particulate material away from the substrate. The electrostatic charged particle trap prevents charged particles from being deposited on the substrate, thereby enabling the deposition of the extremely low-defect-density films required for reflective masks of an extreme ultraviolet lithography system.

Current Isolating Epitaxial Buffer Layers for High Voltage Photodiode Array

Jeffrey D. Morse, Gregory A. Cooper

U.S. Patent 6,452,220 B1

September 17, 2002

An array of photodiodes in series on a common semiinsulating substrate has a nonconductive buffer layer between the photodiodes and the semiinsulating substrate. The buffer layer reduces current injection leakage between the photodiodes of the array and allows optical energy to be converted to high-voltage electrical energy.

Microwave Hemorrhagic Stroke Detector

Waleed S. Haddad, James E. Trebes

U.S. Patent 6,454,711 B1

September 24, 2002

The microwave hemorrhagic stroke detector includes a low-power pulsed microwave transmitter with a broadband antenna for producing a directional beam of microwaves, an index of refraction matching cap to place over a patient's head, and an array of broadband microwave receivers with collection antennas. The system of microwave transmitter and receivers scans around or is positioned up and down the axis of the patient's head. The microwave hemorrhagic stroke detector is a completely noninvasive device designed to detect and localize blood pooling and clots or to measure blood flow within the head or body. The device is based on low-power pulsed microwave technology combined with specialized antennas and tomographic methods. The system can be used for rapid, noninvasive detection of blood pooling that occurs with hemorrhagic stroke in humans or animals as well as for the detection of hemorrhage within a patient's body.

Microfabricated Injectable Drug Delivery System**Peter A. Krulevich, Amy W. Wang**

U.S. Patent 6,454,759 B2

September 24, 2002

A microfabricated, fully integrated drug delivery system capable of secreting controlled dosages of multiple drugs over long periods of time (up to a year). The device includes a long, narrow shaped implant with a sharp leading edge that allows it to be implanted under a person's skin. The implant includes one or more micromachined, integrated, zero-power, high and constant pressure generating osmotic engines; low-power addressable one-shot shape memory polymer (SMP) valves for switching on the osmotic engine and for opening drug outlet ports; microfabricated polymer pistons for isolating the pressure source from drug-filled microchannels; multiple drug-multiple dosage capacity; and anisotropically etched, anatomically sharp silicon leading edge for penetrating the skin during implantation. The device includes an externally mounted controller for the onboard electronics that activate the SMP microvalves of the implant.

Oxidizer Gels for Detoxification of Chemical and Biological Agents**Dennis M. Hoffman, Raymond R. McGuire**

U.S. Patent 6,455,751 B1

September 24, 2002

A gel composition containing oxidizing agents and thickening or gelling agents is used to detoxify chemical and biological agents by application directly to a contaminated area. The gelling agent is a colloidal material, such as silica, alumina, or alumino-silicate clay, which forms a viscous gel that does not flow when applied to tilted or contoured surfaces. Aqueous or organic solutions of oxidizing agents can be readily gelled with less than about 30 percent colloidal material. Gel preparation is simple and suitable for field use because the gels can be prepared at the site of decontamination and applied quickly and uniformly over an area by a sprayer. After decontamination, the residue can be washed away or vacuumed up for disposal.

Awards

Seven Livermore physicists have been named **fellows** of the **American Physical Society (APS)**. This group is among the largest from the Laboratory to be honored in a single year.

The APS Fellowship Program was created to recognize members who have made advances in knowledge through original research and publication or applied physics to make significant and innovative contributions to science and technology. They may also have contributed significantly to the teaching of physics or participated in numerous APS activities.

Tomas Diaz de la Rubia, associate director for Chemistry and Materials Science, was elected for his work in computational physics, notably "his contributions to multiscale modeling of materials and seminal research on defect processes in solids under irradiation or high-strain-rate conditions."

Yu-Juan Chen of the Fusion Energy Division of the Physics and Advanced Technologies (PAT) Directorate was named for her work in revolutionizing the achievable beam quality of linear induction accelerators and advancing the state of the art of flash x-ray radiographic technology.

Forrest Rogers, a physicist in the PAT Directorate who has worked at the Laboratory for more than 30 years, was nominated for his work in plasma physics. He was cited for developing the ACTEX equation of state and OPAL code opacity models and applying them to such astrophysical and laboratory plasma problems as helioseismology, variable stars, and laser shock experiments.

Barbara Lasinski, a long-time physicist in the Defense and Nuclear Technologies Directorate, was cited for "development and applications of particle-in-cell codes for laser-plasma interaction physics and a long series of contributions to the understanding of the physics of targets for high-power laser experiments."

Otto "Nino" Landen, acting associate program leader for ignition physics experiments in the Inertial Confinement Fusion Program of the National Ignition Facility Programs Directorate, was named a fellow for his work in plasma physics, in particular, picosecond laser-plasma interactions, advanced diagnostics, x-ray-driven inertial confinement fusion implosions, and time-dependent hohlraum symmetry control.

Andrew McMahan, a physicist in the PAT Directorate for 28 years, was named a fellow in the computational physics category for his work in completing effective Hamiltonian parameters for copper oxides and phase transitions of materials under high pressure and the subsequent solution of the associated models.

Donald Prosnitz, a physicist in the Nonproliferation, Arms Control, and International Security Directorate who is on leave to serve as chief science advisor for the Department of Justice, was cited for his pioneering work in free-electron lasers, part of the Strategic Defense Initiative. Prosnitz was nominated in the physics and society category for accomplishments in fundamental physics research at Livermore and for his contributions to society through physics research supporting national security and law enforcement technologies.

A Question of Quarks

To learn more about our early universe, scientists are trying to create a state of matter that hasn't existed since the first moments after the big bang. Physicists from Livermore and dozens of other institutions around the world are using the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory to generate this primordial matter, a quark-gluon plasma. Inside the collider, gold nuclei travel at almost the speed of light. When the nuclei collide, they generate huge amounts of energy and millions of new particles.

Measurements from the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector, which Livermore helped to design, are analyzed to determine whether the colliding ions actually created a quark-gluon plasma. Results to date are inconclusive. One set of data based on the volume of the collision zone (or source) indicates that little or no plasma was created, while a relatively low number of high-momentum particles indicates the presence of a plasma. To supply what they hope will be more conclusive data, the Livermore team is adding another detector to PHENIX that can analyze collisions between protons and nuclei.

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Island Paradise Regained

Forty-five years after the cessation of aboveground nuclear testing in the Marshall Islands, Livermore's scientists continue to provide environmental measurement data and dose assessments to Marshallese who wish to resettle their native islands. For more than 25 years, Livermore scientists have conducted a sampling program to evaluate the various exposure pathways for radiological dose. Results indicate that ingestion is the most significant exposure pathway, mostly through uptake of cesium-137 into island-grown foods. To help reduce the dose to returning residents, Livermore developed a two-pronged remediation technique that reduces uptake of cesium-137 into locally grown foods and external radiation exposure to cesium-137. Individual radiation protection programs have been developed that use whole-body counting systems and plutonium urinalysis to assess the intake of radionuclides from residual fallout contamination. Whole-body counting facilities, operated and maintained by Marshallese technicians trained at Livermore, directly measure cesium-137 level in an individual's body. Livermore also developed a measurement technology based on accelerator mass spectrometry that is about 100 times more sensitive in detecting the amount of plutonium in human urine than other techniques.

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A New Code Simulates the Cosmos



With the COSMOS code, Livermore astrophysicists are performing the first three-dimensional simulations of the early moments of the universe, black holes, star formation, and dwarf galaxies.

Also in March

- *Laboratory researchers have developed a lightweight, flexible, foldable space telescope called Eyeglass.*
- *To better understand high explosives, Livermore scientists are developing three-dimensional modeling of the voids and hot spots in explosive materials where ignition begins.*

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